

Time-resolved infrared emission from radiation-driven central obscuring structures in Active Galactic Nuclei

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Accepted . Received ; in original form

ABSTRACT

The central engines of Seyfert galaxies are thought to be enshrouded by geometrically thick gas and dust structures. In this article, we derive observable properties for a self-consistent model of such toroidal gas and dust distributions, where the geometrical thickness is achieved and maintained with the help of X-ray heating and radiation pressure due to the central engine. Spectral energy distributions (SEDs) and images are obtained with the help of dust continuum radiative transfer calculations with RADMC-3D. For the first time, we are able to present time-resolved SEDs and images for a physical model of the central obscurer. Temporal changes are mostly visible at shorter wavelengths, close to the combined peak of the dust opacity as well as the central source spectrum and are caused by variations in the column densities of the generated outflow. Due to the three-component morphology of the hydrodynamical models – a thin disc with high density filaments, a surrounding fluffy component (the obscurer) and a low density outflow along the rotation axis – we find dramatic differences depending on wavelength: whereas the mid-infrared images are dominated by the elongated appearance of the outflow cone, the long wavelength emission is mainly given by the cold and dense disc component. Overall, we find good agreement with observed characteristics, especially for those models, which show clear outflow cones in combination with a geometrically thick distribution of gas and dust, as well as a geometrically thin, but high column density disc in the equatorial plane.

Key words: galaxies: Seyfert – ISM: structure – ISM: clouds – hydrodynamics – radiative transfer – dust, extinction.

1 INTRODUCTION

Active Galactic Nuclei (AGNs) are thought to be powered by accretion onto a supermassive black hole (SMBH, $10^6 - 10^{10} M_{\odot}$). A large fraction of the gravitational energy released by this process is emitted in form of radiation in the ultraviolet (UV) and optical wavelength regime, originating from a viscously heated accretion disc surrounding the SMBH (Shakura & Sunyaev 1973). A fraction of the energy contained in this so-called *Big Blue Bump* in the spectral energy distribution (SED) is absorbed and re-emitted in the infrared (IR) by dust (Rees et al. 1969; Barvainis 1987), which

partly enshrouds the central engine. The latter gives rise to another characteristic feature in the SEDs of AGN – the so-called *IR bump*. The existence of overlaid broad emission lines (tracers of gas close to the central engine) categorises an object as a type 1 source, whereas galaxies with narrow emission lines only are classified as type 2 sources. This observed dichotomy was suggested to be the result of a geometry effect due to a toroidally shaped absorber, usually referred to as the *dusty molecular torus*. In type 1 sources the torus is thought to be seen face-on and in type 2 sources edge-on, where it blocks the direct line of sight towards the centre and only narrow emission lines from gas further out can be detected. This is the essence of the so-called *Unified Scheme of Active Galactic Nuclei* (Antonucci 1993; Urry & Padovani 1995). Indirect evidence for the existence of geometrically

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thick tori comes from the observation of broad emission lines in the polarised flux of type 2 sources. First detected in the nearby Seyfert 2 galaxy NGC 1068 (Miller & Antonucci 1983; Antonucci & Miller 1985), but later also in a sample of other nearby sources (Lumsden, Alexander & Hough 2004), these observations were interpreted as arising from hidden type 1 nuclei. Further indirect evidence and a first estimate of an average opening angle of AGN tori comes from number statistics. Maiolino & Rieke (1995) find a ratio of Seyfert 2 to Seyfert 1 galaxies of 4:1 in their sample, which results in an opening angle of the (more or less) dust-free cones of 74° . This is in line with observations of light cones in nearby Seyfert galaxies. Detailed SED fits for 513 type 1 AGNs from the XMM-COSMOS survey, allowed Lusso et al. (2013) to derive the ratio of re-processed mid-IR emission to intrinsic nuclear luminosity, which is then converted into an obscuration fraction. They find a shallow decrease of the obscuration fraction with increasing AGN luminosity, which seems to be consistent with the so-called *receding torus model* (Lawrence 1991; Simpson 2005) and favours a model where the torus is optically thin in the mid-IR (see also discussion in Sect. 5.4).

Due to their large distances and small sizes, AGN tori appear point-like in direct infrared imaging observations. Only with the advent of mid-infrared interferometry with the help of the MIDI instrument (Leinert et al. 2003) at the Very Large Telescope Interferometer (VLTI) by pairwise combining the light of the 8 m class VLT or 2 m class auxiliary telescopes they could be resolved. Very detailed observations have been carried out for the brightest Seyfert galaxies NGC 1068 (Jaffe et al. 2004; Poncelet, Perrin & Sol 2006; Raban et al. 2009; López-Gonzaga et al. 2014) and the Circinus galaxy (Tristram et al. 2007, 2014). In these cases, the brightness distribution could be disentangled into several components, which resemble an edge-on disc-like structure on sub-parsec scales and an almost round, fluffy or filamentary larger component, probably tracing the torus walls or dust in the torus funnel. In a study of the brightest Seyfert 1 galaxy, NGC 4151, Burtcher et al. (2009) find a similarly sized torus, whereas in the nearest radio galaxy, Centaurus A, most of the nuclear mid-IR emission seems to be of non-thermal origin (Meisenheimer et al. 2007; Burtcher et al. 2010). Apart from NGC 1068 and Circinus, elongations in polar direction (reminiscent of dust in the Narrow Line Region, NLR) have been found in two additional objects, the Seyfert 2 galaxy NGC 424 (Hönig et al. 2012) and the Seyfert 1.5 galaxy NGC 3783 (Hönig et al. 2013). The study of a larger sample of nearby AGN tori within the *MIDI AGN snapshot survey* (Tristram et al. 2009) and the *MIDI AGN Large Programme* (Burtcher et al. 2013) revealed a diversity (but also a number of similarities) of complex, geometrically thick dust morphologies on (sub-)parsec scale. With the help of near-infrared interferometry it is possible to obtain the radius of hot dust close to its sublimation temperature, which seems to scale with the square root of the AGN luminosity as expected (Barvainis 1987; Suganuma et al. 2006; Kishimoto et al. 2011a; Weigelt et al. 2012) and gives us a good measure of the inner radius of the torus. For the case of sizes determined from mid-infrared (MIR) measurements, the scaling with the AGN luminosity and its interpretation is still controversial (Tristram et al.

2009; Tristram & Schartmann 2011; Kishimoto et al. 2011b; Burtcher et al. 2013).

Due to the too low number of visibility measurements, direct image reconstruction is currently not feasible for most sources. Hence, for a careful data interpretation and in order to get a more detailed idea of the structure of the torus, dust continuum radiative transfer simulations for simplified astrophysical scenarios or ad-hoc geometrical models have been carried out and compared to high-resolution SEDs as well as these interferometric observations. Mainly dictated by computational requirements, they started off from simple geometries in which the dust is distributed continuously (Pier & Krolik 1992a, 1993; Granato & Danese 1994; Schartmann et al. 2005; Fritz, Franceschini & Hatziminaoglou 2006). The latter were found to be in good agreement with the gross features of observed SEDs, but continuous tori in general showed too pronounced silicate emission features for type 1 sources. Up to today, only weak silicate emission features have been found in various sources showing AGN activity, ranging from very luminous quasars down to weak LINERS (e. g. Siebenmorgen et al. 2005; Hao et al. 2005; Sturm et al. 2005; Weedman et al. 2005; Hao et al. 2007). This so-called *silicate feature problem* can be solved either by changing the chemical composition of the dust (e. g. Fritz, Franceschini & Hatziminaoglou 2006) or by distributing the dust into clouds. Both approaches can produce comparable strengths of the silicate feature as has been shown by Feltre et al. (2012). However, a distribution of the dust in clouds has the advantage of being more physical as it allows the dust to be protected from sputtering due to the surrounding hot gas (e. g. Krolik & Begelman 1988). Being in reach with today's computational power, clumpy torus (toy) models have been set up (Nenkova, Ivezić & Elitzur 2002; Hönig et al. 2006; Nenkova et al. 2008a,b; Schartmann et al. 2008; Hönig et al. 2010; Hönig & Kishimoto 2010; Stalevski et al. 2012), which partly show good simultaneous agreement with spectroscopic as well as interferometric observations. The wealth and realism of the simulations mentioned above impressively document our gain in understanding of geometrically thick AGN tori. However, several questions remain unanswered: (i) How do tori build up and how do they evolve? (ii) Which processes stabilise the scale height of AGN tori against gravity? (iii) What is the geometrical structure and size of the torus? (iv) Which physical processes generate the required clumpiness?

In early theories, the support was given by clump-clump collisions with a high elasticity, mediated by strong magnetic fields (Krolik & Begelman 1988; Beckert & Duschl 2004). It was also suggested to replace the torus by a magneto-centrifugally driven disc wind solution, in which dusty clumps are embedded (Königl & Kartje 1994; Elitzur & Shlosman 2006; Elitzur & Ho 2009; Czerny & Hryniewicz 2011) and form the so-called *toroidal obscuration region* (TOR), which replaces the classical torus. Already Pier & Krolik (1992b) suggested that AGN tori can be supported by infrared radiation pressure, after the ultraviolet/optical radiation from the central source has been reprocessed within a thin layer at the inner edge of the torus. This idea was successfully tested with the help of analytical calculations in Krolik (2007),

where they simultaneously solve the radiative transfer problem as well as the force balance. The effect of radiation pressure on single dusty torus clouds has been studied in detail by Schartmann, Krause & Burkert (2011), Plewa, Schartmann & Burkert (2013) and Namekata, Umemura & Hasegawa (2014). The implications of a supernova-driven AGN torus is discussed in Wada & Norman (2002) and Wada, Papadopoulos & Spaans (2009), where supernovae (SN) with a rate appropriate for starburst conditions are invoked in a thin disc (following in-situ star formation), which then puffs up the initially rotationally supported thin disc to form a toroidal structure with obscuration properties as observationally determined for AGN tori. The effects of the post-starburst evolution of a young nuclear star cluster as ubiquitously found in nearby Seyfert galaxies (e. g. Davies et al. 2007) on the build-up and evolution of AGN tori has been studied by Schartmann et al. (2009, 2010), being able to explain the feeding and obscuration of AGN tori. The processes at work typically form a two-component structure: a filamentary large-scale torus and a turbulent inner disc component, similar to the findings in the nearest Seyfert galaxies revealed by MIDI. Subsequent radiative transfer calculations enabled to connect this scenario to observations. Recently, another promising model for the build-up of AGN tori in nearby Seyfert galaxies was presented by Wada (2012), which relies on radiation feedback effects (see Sect. 2). It is the aim of this article to connect the density distribution resulting from this model to observable quantities. We attempt to answer whether direct radiation pressure and X-ray heating applied to a self-gravitating disc is able to provide enough turbulent pressure to puff up and sustain AGN tori and whether the structure is consistent with observed properties. This is done with detailed radiative transfer calculations and comparisons to high-resolution observations, where we are for the first time able to provide time-resolved SEDs and images. The parameters are chosen such to represent Seyfert activity (Seyfert 1943), as these are the best studied sources in the local Universe.

The hydrodynamical model itself will be recapitulated in more detail in Sect. 2. After describing the technical methods and details in Sect. 3, the results of the radiative transfer calculations are characterised in Sect. 4. We compare our findings in detail with available observations in Sect. 5, followed up by a critical discussion (Sect. 6) and conclusions are drawn in Sect. 7.

2 THE UNDERLYING HYDRODYNAMICAL MODEL

Wada (2012) proposed a physical model for the build-up of AGN tori with the help of X-ray heating and radiation pressure on dusty gas. To this end, Wada (2012) ran three-dimensional hydrodynamical simulations coupled with the mentioned radiation processes, which are treated with the help of a ray-tracing method and include a $|\cos(\theta)|$ radiation characteristic, mimicking the emission from a thin accretion disc. Additionally, they include the self-gravity of the gas, radiative cooling as well as photoelectric heating due to uniform background UV radiation as well as H_2 for-

mation and destruction. The mass of the central SMBH is chosen to be $M_{\text{BH}} = 1.3 \times 10^7 M_{\odot}$ (see Tab. 1). Together with a time-independent spherical external potential (mimicking the stellar distribution), this results in rotation curves as observed in nearby Seyfert galaxies (see Wada, Papadopoulos & Spaans 2009 for a more detailed description).

Starting with a marginally gravitationally unstable gas disc which has already settled into a flared disc shape (with a total gas mass of the evolved disc of $1.1 \times 10^6 M_{\odot}$), they find that the radiation powers a vertical circulation of gas and dust (“a radiation-feedback-driven fountain”) on parsec to tens of parsec scale, which leads to a toroidal shape of the turbulently moving obscuring material. In the simulations presented in this article, the radiation powers a loss of gas from the computational domain with a rate of $0.1 M_{\odot} \text{ yr}^{-1}$ on average. Hence, in order to keep the structure geometrically puffed-up over typical AGN lifetimes of several tens of Myr, a mass inflow rate from larger scales of the same magnitude is required, which is in the observable range of inflow rates within bars and nuclear spirals (Davies et al. 2014; Storch-Bergmann 2014). Turbulent viscosity within the equatorial plane of the simulated discs then replenishes gas in the innermost region, powering the circular flow pattern. The result of these processes is a multi-phase interstellar medium made up of at least three components: (i) hot, diffuse ionised gas, in which clumps and filaments of (ii) warm molecular gas and (iii) dust are embedded. A smaller Eddington ratio of the central source in general leads to less mass-loaded outflows and hence smaller amounts of gas falling back onto the torus and hence causes less turbulent motions and a geometrically thinner structure. For the purpose of our radiative transfer calculations, resimulations of the two models in Wada (2012) have been carried out, namely for an Eddington ratio of 1 per cent (model ER01) and 10 per cent (ER10). A third model with an Eddington ratio of 20 per cent (ER20)¹ has been added. The computational domain has been decreased by a factor of two, now simulating only a region 32 pc^3 around the centre, but keeping the number of grid cells identical (256^3). The simulation is calculated with self-gravity only until an evolutionary time of 2.5 Myr. Self-gravity in combination with thermal instability leads to filamentary/spiral-like structures within the differentially rotating disc (Wada 2001). These structures cannot survive over many rotational periods (0.1-1 Myr), but similar structures are always reformed due to the instabilities since the disc is kept at low temperatures by the radiative cooling. Therefore, the entire filamentary morphology is long-lived over several Myr. After 2.5 Myr, the radiation is switched on and the first snapshot we use in this article is recorded after 0.1 Myr. A total of 20 snapshots are used with a time difference of 0.1 Myr. Following Wada (2012), we translate the gas density to a dust density distribution by applying a dust-to-gas mass ratio of 0.03 (Ohsuga & Umemura

¹ We note that the Eddington ratios given here do not take the radiation characteristic of the central source into account. “Effective” Eddington ratios can be calculated by applying an angle average: $\frac{\int_0^{\pi/2} L_{\text{AGN}} \cos(\theta) d\theta}{\int_0^{\pi/2} d\theta} = 2/\pi$. This then translates to Eddington ratios of 0.6 per cent (ER01), 6.4 per cent (ER10) and 12.7 per cent (ER20).

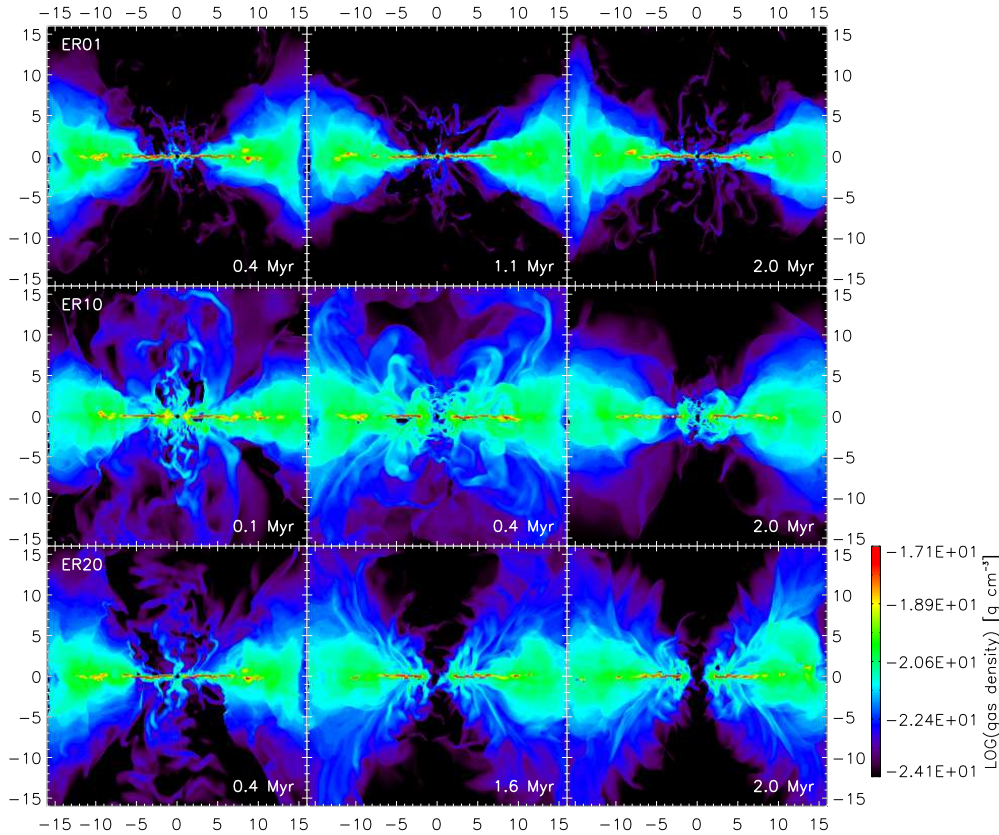


Figure 1. Cut through the $y=0$ plane of the gas density distribution for three characteristic time steps for models ER01 (upper panel), ER10 (middle panel) and ER20 (lower panel). A time of 0 Myr corresponds to the switching on of the nuclear radiation. Labels are given in parsec. See Wada (2012) for a detailed description of the dynamical evolution.

2001) for all gas with a temperature below 10^5 K. In regions with a gas temperature above 10^5 K, the dust density is set to zero. This is the temperature threshold where silicate and graphite grains get destroyed on short time scales, caused by sputtering processes due to the surrounding hot gas (Dwek, Foster & Vancura 1996).

Fig. 1 shows a sequence of time snapshots for meridional slices through the gas density distribution of the three models (ER01 – first row, ER10 – second row and ER20 – third row). There are already clear differences in the appearance visible: model ER01 is not able to puff up the central few parsec regime significantly; only an intermittent, low-density outflow builds up. Model ER10 generates a geometrically thick structure on parsec scale already early on (0.1 Myr after switching on the radiation source) including an outflow with a relatively high mass-loading factor. Already after 0.4 Myr, the outflow ceases and the central region remains gas and dust enshrouded until the end of the simulation. The void conical structure at the latest displayed snapshot is a consequence of the inflow motion at larger distances from the midplane beyond the central gas enshrouded region. In contrast, model ER20 is able to create a steady outflow with a very low gas and dust density within the outflow-cone. However, the intermittent nature of the outflow and energy feedback respectively is visible in the filamentary, outward-moving structures. The latter have velocities of the order of 100 km s^{-1} and therefore remain within the computational

domain for roughly 0.1 Myr. As soon as the model reaches a steady state, they are constantly formed in the central region. We cut out a central sphere with a radius of 1 pc for the radiative transfer calculations, necessitated by the applied smoothing of the gravitational forces in the central few cells in the hydrodynamical calculation (see discussion in Sect. 6). The behaviour described above is quantified by displaying the optical depth at $0.55 \mu\text{m}$ as a function of viewing angle (face-on to edge-on). To this end, we determine the optical depth along 1000 randomly chosen radial rays. The average of these rays per viewing angle bin of 5° is shown in Fig. 2 for the first time snapshot (upper panel) and the last one (lower panel). Whereas model ER01 shows the characteristic distribution for a thin disc for all snapshots, both models ER10 and ER20 develop into a thick toroidal structure for viewing angles close to edge-on viewing. Different from model ER10, which develops a highly mass-loaded and later ceasing outflow from the beginning, model ER20 is able to create a low-density outflow cone.

3 THE RADIATIVE TRANSFER MODELLING APPROACH

For our dust continuum radiative transfer calculations, we make use of the versatile three-dimensional Monte-Carlo-

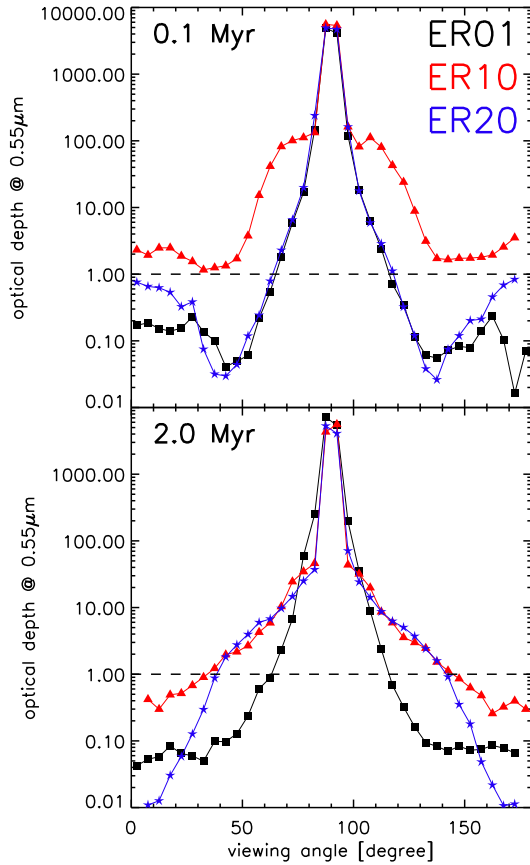


Figure 2. Optical depth at $0.55\mu\text{m}$ as a function of viewing angle, where 0° and 180° correspond to face-on lines of sight and 90° to an edge-on view. Displayed are the models ER01 (black squares), ER10 (red triangles) and ER20 (blue stars) at two time snapshots: 0.1 Myr (upper panel) and 2.0 Myr (lower panel) after switching on the central radiation source. The dashed lines show the limiting optical depth used to determine the obscured fraction in Fig. 12.

Code RADMC-3D². We directly apply it to the three-dimensional cartesian grid described in Sect. 2. Apart from the ability to calculate dust continuum radiative transfer, which is used in our simulations, it also includes modules for gas line transfer and gas continuum transfer. We use a typical galactic dust model as described in Schartmann et al. (2005), where the dust is split into 5 different grain sizes (following an MRN size distribution, see Mathis, Rumpl & Nordsieck 1977) for the three different grain species each: silicate and the two orientations of graphite grains with optical properties adapted from Draine & Lee (1984), Laor & Draine (1993) and Weingartner & Draine (2001). The dust is heated by the central source, which is modelled as a point-like emitter with a $|\cos(\theta)|$ radiation characteristic, where θ is the polar angle counted from the rotation axis. The assumed spectral shape of the central source is identical to the one used in Schartmann et al. (2005), which was constructed from a combination of observations and expected cut-offs from the-

Table 1. Model parameters of the simulations.

M_{BH}	$1.3 \times 10^7 M_\odot$	$M_{\text{gas,ini}}$	$1.1 \times 10^6 M_\odot$
ϵ_{Edd}	0.01 (ER01)	L_{source}	$4.2 \times 10^9 L_\odot$
	0.1 (ER10)		$4.2 \times 10^{10} L_\odot$
	0.2 (ER20)		$8.5 \times 10^{10} L_\odot$
f_{drg}	0.03	$T_{\text{gas,thresh}}$	10^5 K
n_{lam}	300	n_{phot}	10^8
$n_{\text{phot,scat}}$	10^6	$n_{\text{phot,spec}}$	10^4
x_{max}	16 pc	R_{in}	1 pc

M_{BH} is the central black hole mass, $M_{\text{gas,ini}}$ is the total gas mass at the time the radiation is switched on, ϵ_{Edd} is the Eddington ratio, L_{source} the corresponding luminosity of the central source, f_{drg} the dust-to-gas ratio, $T_{\text{gas,thresh}}$ the threshold gas temperature for dust to survive, n_{lam} the number of wavelengths for the calculation of the temperature distribution as well as the SEDs, n_{phot} the number of photon packages used in the thermal Monte-Carlo run, $n_{\text{phot,scat}}$ the number of photon packages to calculate the scattering in images (this number has been increased for the case of the images at $0.1\mu\text{m}$ to 10^8), $n_{\text{phot,spec}}$ the number of photon packages for the calculation of scattering in the SEDs, x_{max} the half side length of the computational box and R_{in} is the inner radius for the radiative transfer calculation. For a detailed description of the model parameters of the hydrodynamical simulations, we refer to Wada (2012).

oretical models for accretion discs. After a thermal Monte-Carlo simulation (Bjorkman & Wood 2001; Lucy 1999), in which anisotropic scattering is treated using the Henyey-Greenstein approximate formula, the resulting dust temperature distribution is used to calculate images at various wavelengths as well as SEDs. Given the large necessary inner radius (see Sect. 2), not all dust grains reach their sublimation temperatures. This especially has some consequences for the near-IR (NIR) emission from the dust structure, as discussed in detail in Sect. 6. The basic parameter settings of our radiative transfer models as well as the underlying hydrodynamical models are given in Table 1.

4 RESULTS OF THE RADIATIVE TRANSFER SIMULATIONS

4.1 The wavelength dependent appearance of the obscuring structure

Fig. 3 shows the inclination angle (from face-on – column 1 to edge-on – column 4 in steps of 30°) and wavelength ($0.1\mu\text{m}$ – upper row, $12\mu\text{m}$ – middle row and $500\mu\text{m}$ – lower row) dependence of the ER20 model at a time of 2.0 Myr. Looking first at the mid-infrared images (middle row) one can clearly see that it changes from a centrally symmetric structure to something more and more asymmetric. At higher inclinations, high-column-density filaments from close to the equatorial plane become visible in form of dark absorption bands and partly end up on the line of sight. Already at $i = 30^\circ$ they can be seen against the background of the emission from the low density dust in the funnel region and its directly illuminated walls. The latter becomes the dominant structure in the edge-on and near edge-on view, where it turns into an X-shaped feature. The appearance is significantly different at short wavelengths. Shown in the upper row of Fig. 3 is the intensity at $0.1\mu\text{m}$, corresponding

² <http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/>

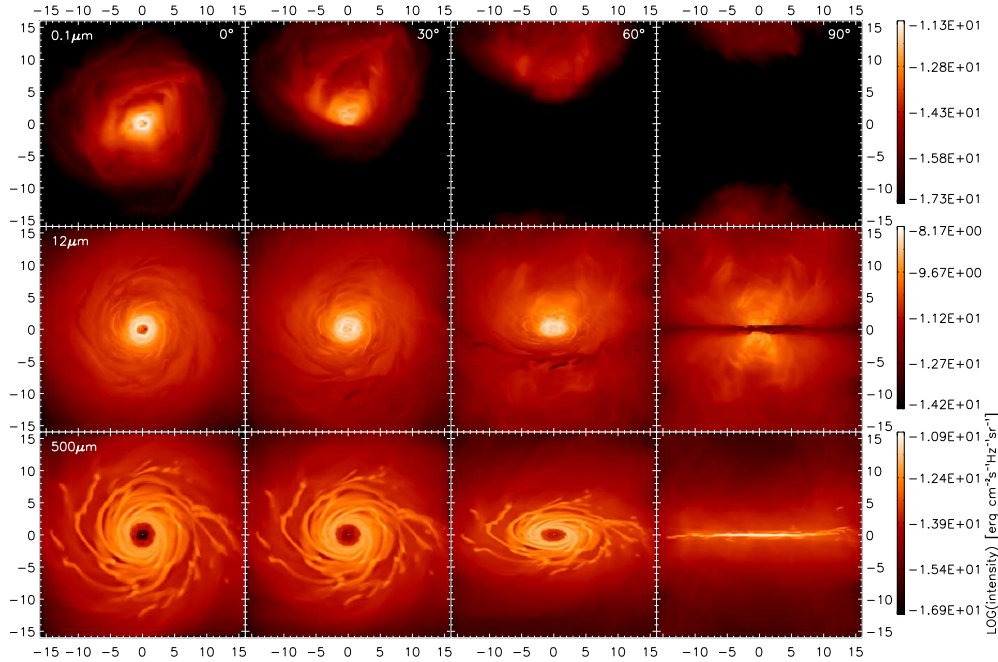


Figure 3. Wavelength dependence of model ER20 at a time 2.0 Myr after the central radiation has been switched on. The various columns correspond to inclination angles of 0° , 30° , 60° and 90° (from left to right). The rows correspond to wavelengths of $0.1\,\mu\text{m}$ (upper row), $12\,\mu\text{m}$ (middle row) and $500\,\mu\text{m}$ (lower row). The dynamic range is chosen to scale from the maximum intensity of dust emission (excluding the central source) down to the 10^{-6} th fraction of it. Labels are given in parsec.

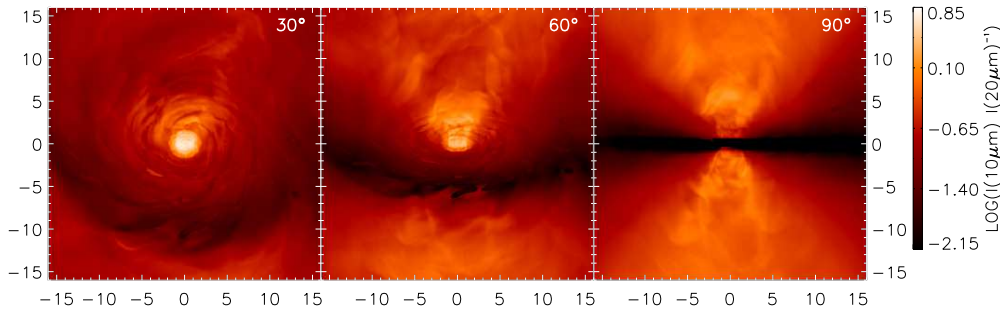


Figure 4. Ratio of intensity maps at a wavelength of $10\,\mu\text{m}$ and $20\,\mu\text{m}$ – indicative of dust temperature – of model ER20 at a time 2.0 Myr after the central radiation has been switched on, where brighter colours correspond to higher temperatures. The panels correspond to inclination angles of 30° , 60° and 90° (from left to right). The dynamic range is chosen to scale from the maximum ratio down to the 10^{-3} rd fraction of it. Labels are given in parsec.

to the maximum emission of the central source. The visible structures are dominated by scattered light as well as absorption, as this is also the peak of the opacity model used (see Sect. 3 and compare to Fig. 3a in Schartmann et al. 2005). Due to the high absorption efficiency, only scattered light from the low-density cones is visible. Please mind the orders of magnitude difference in the intensity compared to the other wavelengths shown (see colour bars). The lower-most row displays images at $500\,\mu\text{m}$. In this case, the emission is dominated by dust at very low temperatures. Additionally, the opacity has dropped dramatically in this wavelength regime. Hence, the largest fraction of the obscuring structure itself is optically thin and only the high-density disc with spiral-like features in the midplane of the simulation shows up. Such structures are ubiquitous in imag-

ing observations and dust extinction maps (Sect. 5.1). The emerging multi-component structure can best be seen in the ratios of the brightness distributions at $10\,\mu\text{m}$ and $20\,\mu\text{m}$, which is displayed for three inclination angles in Fig. 4. The hot dust (brighter at $10\,\mu\text{m}$) is concentrated close to the centre, as well as within the low-density outflow cones. Towards the midplane, the disc gets colder and colder and dominates the longer wavelength emission (darker colours). This multi-component nature of the central gas and dust distribution is clearly not very well captured by the term “torus”. Therefore, we will replace it in the following by “obscuring structure” or similar.

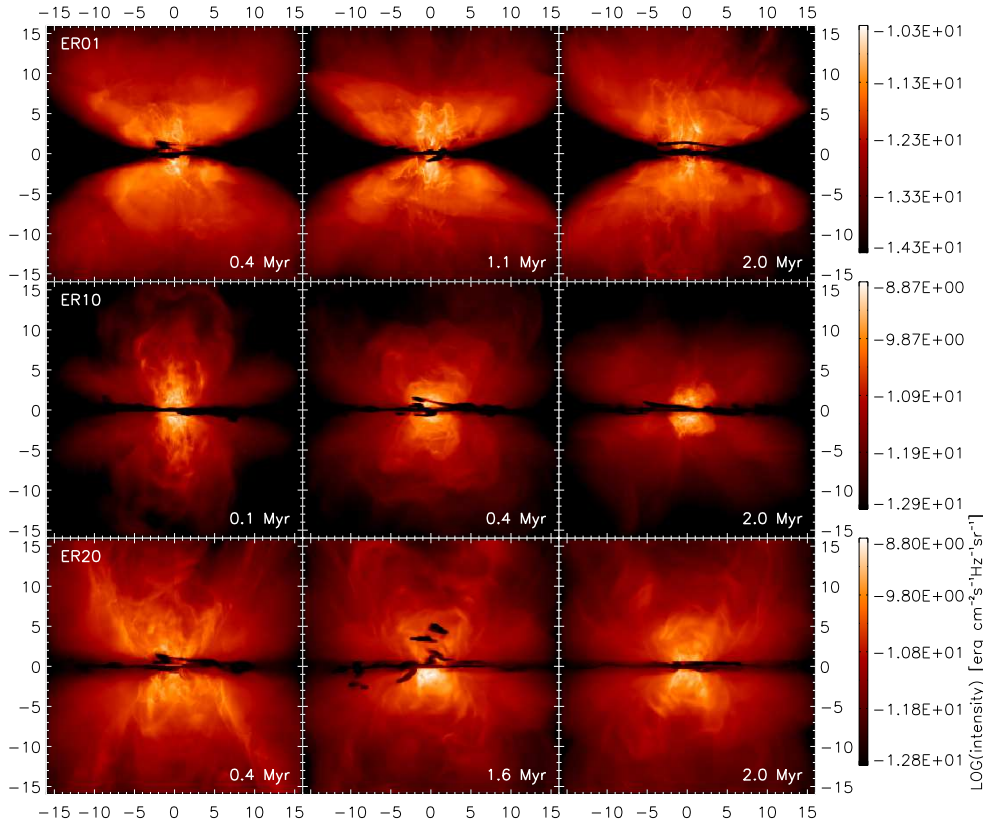


Figure 5. MIR images at $12\mu\text{m}$ of the three characteristic time steps shown in Fig. 1 for models ER01 (upper panel), ER10 (middle panel) and ER20 (lower panel). Shown is the edge-on view ($i = 90^\circ$). Labels are given in parsec.

4.2 Time evolution of mid-infrared images

The same timesteps as shown in the gas density distributions in Fig. 1 and discussed in Sect. 2 are shown in Fig. 5. As already detailed above, for the case of model ER01 (upper row), the radiation is not able to significantly increase the disc scale height. Only a filamentary, low-density outflow arises, which clearly shows up in the $12\mu\text{m}$ images. Due to the low densities above and below the disc and the non-existence of a small scale obscuring structure, the emission cone has a comparatively large opening angle. The dense filamentary disc shows up in form of a central absorption band, strengthened by the applied $|\cos\theta|$ radiation characteristic. Model ER10 (middle row) represents an example, which starts with a high column density filamentary outflow (see Fig. 2), leading to a vertically elongated appearance of the edge-on view onto the dust distribution. At later snapshots, the outflow ceases, resulting in a temporary X-shaped emission (middle panel) and later in a centrally concentrated and spherically symmetric morphology (right panel). The model ER20 (lower row) shows the strongest outflow, visible in the formation of a low density, but inhomogeneous funnel and hence the funnel walls can be more or less directly heated from the central source, showing up as X-shaped features (see Sect. 5.1), especially in the first displayed snapshot. At later times, the initially thin disc gets puffed-up more and more leading to a decreasing opening angle of the funnel. In some snapshots, the absorption due to high density clumps leads to an asymmetric appearance

of the dust configuration. An example can be seen in the middle panel.

4.3 Time-resolved spectral energy distributions

Fig. 6 shows a compilation of SEDs of all models and time steps discussed in this article. The different panels refer to the three Eddington ratios taken into account: from 1 per cent (upper panel, ER01) to 10 per cent (middle panel, ER10) and 20 per cent (lower panel, ER20). Inclinations are colour-coded (black solid - $i = 0^\circ$, face-on, blue dotted - $i = 30^\circ$, green dashed - 60° , red dash-dotted - 90° , edge-on), where the thin lines in light colour refer to the individual SEDs from the time series and thick lines show the SEDs averaged over the available time steps. In general two bumps are visible: (i) the “Big Blue Bump” – peaking at roughly $0.1\mu\text{m}$ – and (ii) the “IR bump”, peaking at around $10\mu\text{m}$. The first represents the SED of the central source, which acts as the only source of energy in our simulations (see Sect. 3 and Fig. 3b in Schartmann et al. 2005 for details). It is partially absorbed due to dust on the line of sight and slightly altered by scattering off dust grains. Heating the surrounding dust to temperatures close to the sublimation temperature results in re-emission of the grains in the infrared wavelength regime, visible in the form of the “IR bump”. Overlaid over the two bumps are spectral features: most prominent and also most important for our analysis is the *10 micron feature* (peaking more accurately at $9.7\mu\text{m}$, see discussion in

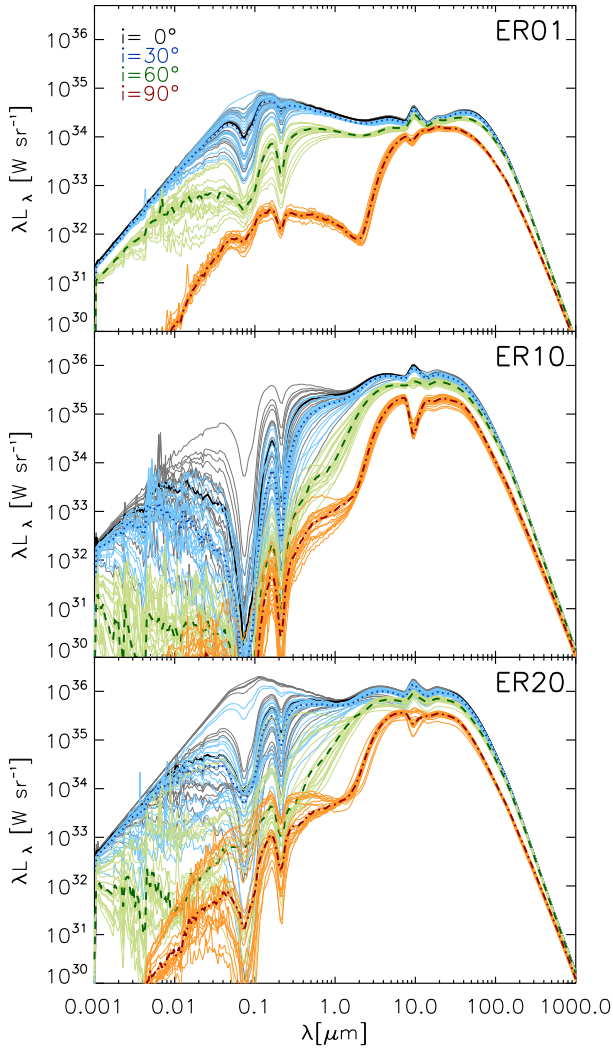


Figure 6. Time evolution of the SEDs of model ER01 (upper panel), ER10 (middle panel) and ER20 (lower panel). The thick lines represent the median of all time snapshots of the respective models at inclinations of 0° (black solid), 30° (blue dotted), 60° (green dashed) and 90° (red dash-dotted). SEDs of the individual snapshots are given in lighter colour.

Sect. 5.3), arising due to stretching modes in silicate tetrahedra (Si-O stretching modes). Only slightly visible is the second resonance of silicate dust, namely the $18.5\,\mu\text{m}$ feature (attributed to O-Si-O bending modes). The very pronounced absorption feature at around $0.08\,\mu\text{m}$ has contributions both from the small graphite grains and small silicate grains. At $0.2175\,\mu\text{m}$, graphite shows a significant feature. Given the temperature constraints at these wavelengths, the latter only show up as absorption features against the background of the flux from the central source SED. As the dust extinction properties as well as the central source SED peak at roughly $0.1\,\mu\text{m}$, dust gets heated very efficiently to temperatures up to the sublimation temperature (approximately $1500\,\text{K}$ for graphite grains and $1000\,\text{K}$ for silicate grains). When inclining the toroidal structure from face-on view towards edge-on view (black solid \rightarrow blue dotted \rightarrow green dashed \rightarrow red dash-dotted), more and more cold dust

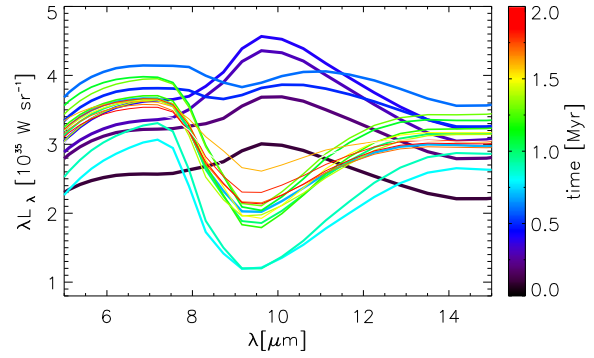


Figure 7. Time evolution of the silicate $9.7\,\mu\text{m}$ feature in the SEDs of model ER20 for an inclination angle of 90° . The line colours refer to various evolutionary stages as indicated in the colour bar. Line thickness decreases from the first snapshot to the last.

moves into the line of sight towards the nucleus. The resulting absorption is most visible around the peak of the opacity curve ($0.1\,\mu\text{m}$, see e.g. Schartmann et al. 2005) and the graphite (and silicate) resonances show up as absorption feature. Also the overall emission in the IR bump decreases due to the increasing absorption along the line of sight. The biggest difference is visible between 60° and 90° inclination angle, due to the remaining large column densities within the equatorial plane when looking exactly edge-on onto the dust distribution. This effect is strongest for model ER01, as expected for a geometrically thin disc. ER10 shows the deepest absorption features, caused by the compact density distribution of the failed wind. Model ER20 results in the largest differences at short wavelengths, caused by the already mentioned three-component structure: disc, obscuring structure and outflow. It is also noteworthy to mention that model ER20 shows a variety of feature strengths at the various time steps for the edge-on case (see the zoomed-in view of the SEDs in Fig. 7): The silicate feature changes from slight emission (partly self-absorbed) during the early evolution (black to blue thick lines) when the structure is still disc-dominated, to strong absorption during the high-density outflow phase (cyan intermediately thick lines) to the final steady state with moderate absorption (green to red thin lines), which is reached after roughly $1.6\,\text{Myr}$ (compare to the light curve shown in the lower panel of Fig. 8). The variation of the silicate absorption feature in the quasi-steady state gives a hint towards the clump size distribution or the contribution of hot dust within the funnel. The majority of our modelled SEDs show emission features, even for inclinations as high as 60° (see discussion in Sect. 5.3).

4.4 Light curves

Fig. 8 shows light curves for the three models for wavelengths of $0.1\,\mu\text{m}$ (squares), $12.0\,\mu\text{m}$ (stars) and $500.0\,\mu\text{m}$ (triangles) at inclination angles of 30° (blue) and 90° (red). The $500.0\,\mu\text{m}$ (triangles) light curve traces the cold dust component, e.g. the dense disc only. As the latter remains in a quasi-steady state, a constant time evolution can be observed for all three models during the $2\,\text{Myr}$ time frame. At this wavelength, the obscuring structure is optically thin

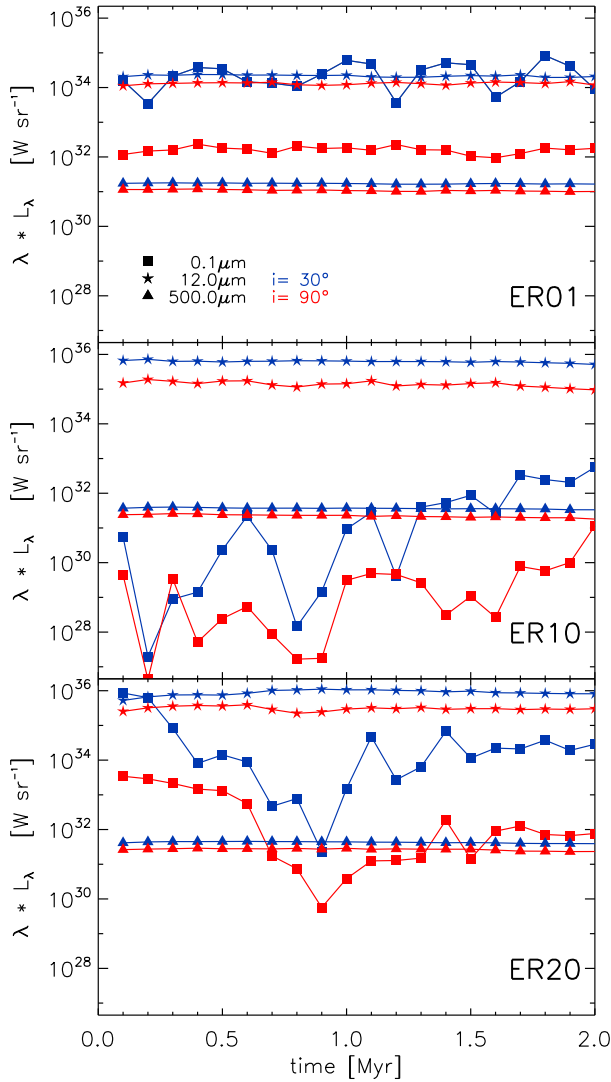


Figure 8. Light curves for the models ER01 (upper panel), ER10 (middle panel) and ER20 (lower panel) for wavelengths of $0.1\,\mu\text{m}$ (squares), $12.0\,\mu\text{m}$ (stars) and $500.0\,\mu\text{m}$ (triangles) at inclination angles of 30° (blue) and 90° (red).

for all calculated inclinations ($0^\circ, 30^\circ, 60^\circ, 90^\circ$), except for a slightly lower luminosity for the edge-on view. This is the expected result for a thin disc. For the case of the $12.0\,\mu\text{m}$ light curve (stars), model ER01 shows the same behaviour, but for the other two models, the flux decrease with inclination is slightly stronger, as expected. At the shortest probed wavelength of $0.1\,\mu\text{m}$ (squares), the differences between the inclinations are the highest, because this is at the maximum of the opacity curve. At these wavelengths only scattering off dust grains can act as a source term apart from the primary radiation. The relatively constant time evolution of model ER01 is indicative of the low density (and hence optical depth) of the lifted dust. Furthermore, no strong clumpiness exists in this model. In model ER10, the outflow ceases relatively early on, but compared to the other two models, no steady state solution is reached. Instead, during the further evolution, the column density towards the poles slightly decreases with time (see Fig. 2), which is

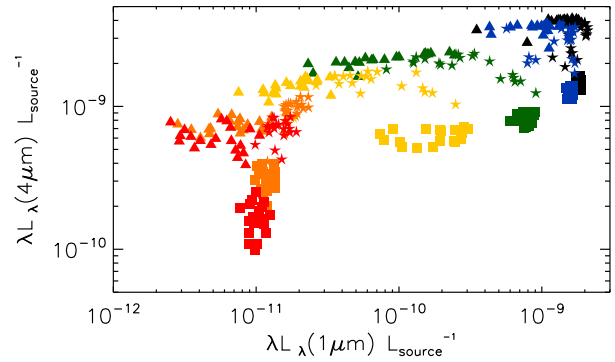


Figure 9. Colour-colour diagram for models ER01 (squares), ER10 (triangles) and ER20 (stars) at inclination angles of 0° (black), 30° (blue), 60° (green) and 90° (red). Intermediate inclination angles are given in yellow (70°) and orange (80°). All 20 time steps are shown for each model and inclination.

reflected in the rising trend of the short wavelength light curve. Finally, this behaviour might lead to a periodical re-establishment of an outflow along the axis, as can be seen in the time-evolution of the same model in Wada (2012). In contrast, model ER20 shows a dip, correlated with an episode of strong and dense outflows, emphasizing the intermittent behaviour of the model.

4.5 Evolution in the colour-colour diagram

Fig. 9 shows a colour-colour diagram, where the emission at $4\,\mu\text{m}$ is compared to emission at $1\,\mu\text{m}$. Model ER01 (represented by the squares) clearly shows distinct concentrations for every inclination angle (due to the applied radiation characteristic), with only small time variations: strong 1 and $4\,\mu\text{m}$ emission for inclinations up to 60° and at low luminosities for both wavelengths for near edge-on views. Between 60° and 90° , first the $1\,\mu\text{m}$ flux decreases (yellow squares, $i = 70^\circ$) and later also the $4\,\mu\text{m}$ flux (orange squares, $i = 80^\circ$), dictated by the shape of the opacity curve. In total it resembles a broken power law distribution. This is the expected signature for a geometrically thin disc with a sharp, discontinuous evolution from a type 1 to a type 2 source. For the case of models ER10 and ER20, a similar behaviour is seen, but shifted towards higher $4\,\mu\text{m}$ fluxes. In a geometrically thick structure, a larger fraction of the primary radiation intercepts with dust and is re-emitted in the IR. The maximum flux at $1\,\mu\text{m}$ is roughly the same for all models, due to the normalisation by the total input luminosity. The distribution of the individual inclinations of the two models along the x-axis is much more stretched compared to ER01, which reflects the stronger time-dependence of those models resulting in a real fountain process with higher density clumps embedded. It is, however, strongest for ER10 which is caused by the intermittency of the outflow, finally resulting in a failed wind, which enshrouds the nucleus.

5 COMPARISON WITH OBSERVATIONS

After having characterised the observable appearance of the models, we will do a first comparison with available observational data in the following.

5.1 Imaging observations of nearby Seyfert galaxies

Recent imaging observations of the best studied nearby low luminosity galaxies with ground-based 8m-class and space-based telescopes reveal striking similarities to our simulated images. These studies reach the currently highest possible resolutions and typically image the tens of parsec surrounding of the central SMBH. To this end, they are not directly comparable in size to our simulations, but a continuation of the structures found there might be expected, as we will motivate in the following. The mentioned X-shaped morphology at MIR wavelengths, which is mainly seen for model ER20 in Fig. 5 (lower row) can be recovered in the observations of the Circinus galaxy analysed by Prieto et al. (2004), see especially their multi-wavelength image (their Fig. 2). Here, the V-shaped structure marks the transition to the *one-sided ionisation cone*. The observed central K-band source would then correspond to our central, directly illuminated core region. A similar *tongue-like* appearance is also found in the parsec-scale vicinity of NGC 1068 in form of the so-called UV cloud B (Evans et al. 1991), compare also to Fig. 3 (bottom left) in Prieto et al. (2014, hereafter P14). In these cases, the low extinction within the strong, but low-density outflow (as found in model ER20) enables the scattered light to be visible (Fig. 3, upper row) and the escape of coronal lines. A multitude of such *ionisation cones* have been observed in nearby sources. They are supposed to be caused by the main obscurer on (sub-)parsec-scale and hence expected to extend from (sub-)parsec up to hundreds of parsec scale. Indeed, dust emission along the direction of the ionisation cones is also detected on parsec-scales in the interferometric observations with the MIDI instrument (Tristram et al. 2014; López-Gonzaga et al. 2014). The behaviour of our models (especially ER20) at wavelengths of 0.1 μm and 12 μm at inclination angles $i \geq 60^\circ$ (Fig. 3) is reminiscent of the observed flux distribution of the Seyfert 2 galaxy MCG 05-23-016. Two cones of emission are visible in the optical wavelength regime in combination with an extinction lane (see Fig. 2 mid left panel in P14). The latter is even better visible in the dust extinction map as shown in their Fig. 2 (mid right panel). The dust extinction maps are a convenient way of imaging the morphology of warm dust with respect to the background galaxy light. In this sense, they can – from a morphological point of view – be compared to our emission maps of the warm dust, e. g. at 12 μm . Spiral-like features and filaments – as revealed in our long wavelength images (Fig. 3, lower row) – are ubiquitous structures in the cores of nearby active galaxies, which have recently also been detected in dust extinction maps, but on slightly larger scales (dictated by resolution constraints). Prominent examples are NGC 1097 (see Fig. 5 in Prieto, Maciejewski & Reunanen 2005) and ESO 428-G14 (see Fig. 1 in P14). In summary, similar filamentary structures to the ones predicted by our simulations in the parsec-scale vicinity of the central engine are already

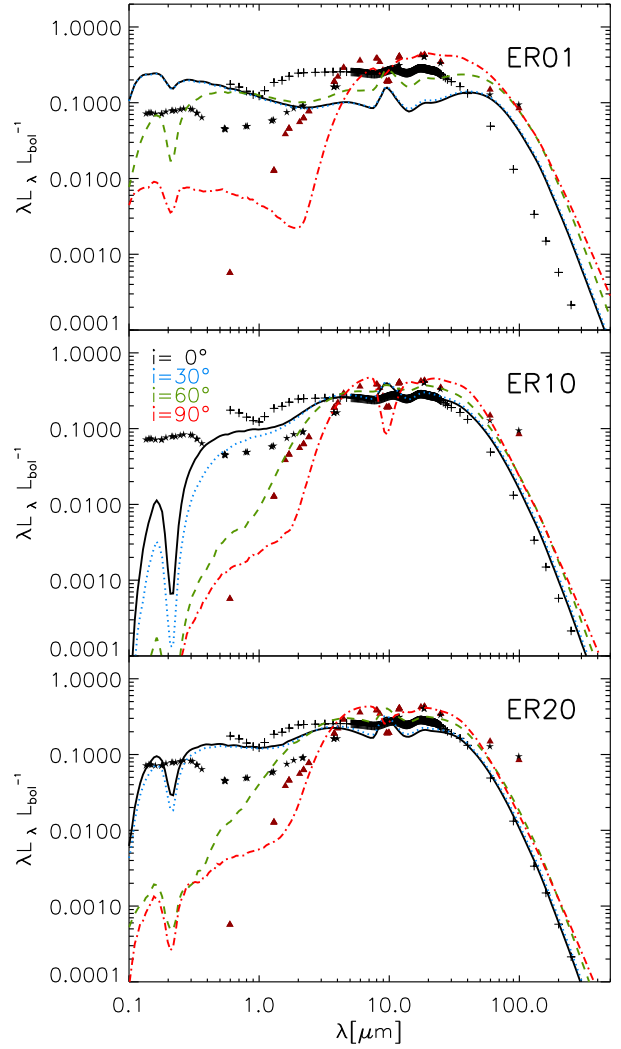


Figure 10. Comparison of model SEDs to the observed templates for Seyfert 1 galaxies (black stars) and Seyfert 2 galaxies (red triangles) of Prieto et al. (2010) as well as the composite type 1 SED of Mor & Netzer (2012), given by the black plus symbols. All SEDs are normalised to their total bolometric luminosity L_{bol} , but are otherwise the same as the ones shown in Fig. 6: ER01 (upper panel), ER10 (middle panel) and ER20 (lower panel) at inclinations of 0° (black solid), 30° (blue dotted), 60° (green dashed) and 90° (red dash-dotted). Only the median SEDs of all time snapshots of the respective models are shown.

observed in extinction maps on the smallest resolvable scales (corresponding to the tens of parsec central regions of nearby Seyfert galaxies). Future observations will be able to test our predictions for even smaller scales.

5.2 The average nuclear SED in Seyfert galaxies

Fig. 10 shows the time-averaged SEDs of all models normalised to their total bolometric luminosity L_{bol} (see Fig. 6 for the original SEDs). This is done in order to enable a comparison with high spatial resolution observed templates for Seyfert 1 (black stars) and Seyfert 2 (red triangles) galaxies (Prieto et al. 2010, hereafter P10). The latter have been normalised to their total emission of the IR and UV bumps as

well, within the wavelength regime between 0.1 and 100 μm . Although the Seyfert templates rely on low-number statistics (three type 1 sources and four type 2 sources are included in the average, see P10) and a large variety of spectral shapes are observed, they give us the best current estimate of the core SED of Seyfert galaxies – i. e. medium to high luminosity AGNs. Due to their high spatial resolution, they represent the intrinsic AGN plus central dust SED and, hence, allow a direct comparison with our modelling. We additionally show the composite SED from Mor & Netzer (2012, hereafter MN12), which has been recently extended towards shorter wavelengths (Netzer, private communication) as the black plus symbols. It is in good agreement with the Elvis et al. (1994) template, with only larger deviations at far-infrared (FIR) wavelengths. The MN12 template has also been normalised to its total luminosity within its available wavelength range (0.6–250 μm). It is an average of 51 narrow-line Seyfert 1 galaxies (NLS1s) and 64 broad-line Seyfert 1 galaxies (BLS1s) with a large variety of luminosities, observed with *Spitzer*. Given the large beam size, the star formation contribution has been subtracted with the help of star formation templates, taking into account the full range of possible host galaxy properties. This template is slightly bluer compared to the one of P10 (black stars), with the largest deviations corresponding to roughly a factor of two higher luminosities in the NIR. We attribute the latter to a combination of a higher level of extinction along the line-of-sight of the Seyfert 1 galaxies in the P10 sample and to the contribution of luminous objects (PG quasars) that may dominate the MN12 sample in this wavelength regime. As expected, model ER01 neither gives a good match to the type 1 nor the type 2 templates. Concerning the type 2 template, the models either show too little extinction (0° to 60°) or a deficiency of flux in the NIR at 90° . A good match can only be expected for a very narrow range in inclination angle. The models overpredict the long wavelength emission and the silicate feature in absorption is not as pronounced as in the observations. A detailed comparison for the type 1 sources is more difficult due to the discrepancy of the observed composite SEDs. However, an extinction comparable to the sources in the P10 template can only be achieved for inclinations larger than 60° , which is unrealistic for type 1 nuclei. In addition, the models are neither in good agreement with the MN12 template, as they show a deficiency of emission in the NIR. The models also tend to produce too much emission at longer wavelengths. The reason for this behaviour is the morphology of the model, which is dominated by the thin and dense disc (see Sect. 2).

A better match with the data is found for model ER10. However, most of the time snapshots show more extinction than observed at short wavelengths ($\lambda < 0.3\mu\text{m}$), even for the case of the P10 type 1 template. The fully edge-on view shows on average a too pronounced silicate absorption feature. This behaviour is expected for this model, as – due to the failed outflow – the central core is fully enshrouded with dust, leading to the highest column densities in polar direction of all models (Fig. 2).

Model ER20 results in a reasonably good comparison of the edge-on models with the observed type 2 template. The apparent discrepancy at wavelengths around $2\mu\text{m}$ (and related to this the uncertainty in this wavelength regime due to our choice of a large inner radius) is mitigated by the

fact that the scatter of the SEDs combined in the type 2 template is larger than the visible *knee* structure, which is bracketed by the simulated SEDs for 60° and 90° inclination. Surprisingly, even the silicate absorption feature depth is roughly reproduced on average. At the largest simulated wavelengths (where the obscuring structure is more or less optically thin), the SEDs show too little flux compared to the P10 templates, but are in rough agreement with the MN12 template. The differences in the templates in this wavelength regime most probably arise from differences in the treatment of the subtraction of starburst contributions, spatial resolution as well as the sample. As already mentioned, the P10 average SED is made up of Seyfert galaxies only, the MN12 one is dominated by quasars, which on average have higher Eddington ratios compared to local Seyfert galaxies. This also appears to be reflected in our Eddington ratio study, giving a better comparison of the ER20 model to the MN12 template and resulting in a closer match of the low Eddington ratio models to the P10 template. Concerning Seyfert 1 observations, the majority of the ER20 models seem to reproduce the correct absorption at around $0.2\mu\text{m}$ and show NIR emission in-between the P10 and MN12 templates. However, a clear deficiency of our models is the emergence of deep graphite features at $0.2\mu\text{m}$, which are never seen in observations. This is an unsolved problem related to the dust model used in our simulations. The NIR is also the spectral range where our models suffer from the largest uncertainties. First of all, our relatively large inner radius does not allow all dust grain species to reach their sublimation temperature on the one hand. On the other, the cut out dust does not contribute to extinction and clumpiness on small scales, which causes a larger fraction of hotter dust in the outflow cone. The latter also depends on the assumed dust-to-gas fraction, which might be spatially varying and significantly reduced in the hot outflow cones. Additionally, in this region, the choice of the central source spectrum can also play a role. All three model families show too strong silicate emission features (see also discussion in Sect. 5.3).

We conclude that the overall best adaptation of the observations is given by model ER20, leading to the conclusion that a three-component structure made up of a high column density thin disc plus a geometrically thick surrounding atmosphere, which collimates a low density outflow, is capable to explain these observational constraints and replaces the classical “torus” in this model.

5.3 The silicate feature strength / column density relation

In Fig. 11, the silicate feature strength is shown as a function of the neutral hydrogen column density. To calculate $N_{\text{H I}}$, only cells with a gas temperature below the ionisation temperature of hydrogen (1.7×10^4 K) are integrated along the given line of sight. The strength of the silicate feature is determined in analogy to Shi et al. (2006) as

$$\Delta_{\text{feature}} = \frac{F_{\text{feat}} - F_{\text{cont}}}{F_{\text{cont}}}, \quad (1)$$

where F_{feat} is the flux at the wavelength of the silicate feature (taken where the maximum deviation from the continuum is reached) and F_{cont} is the spline fitted continuum at the same position, anchored at wavelengths between 5.0 and

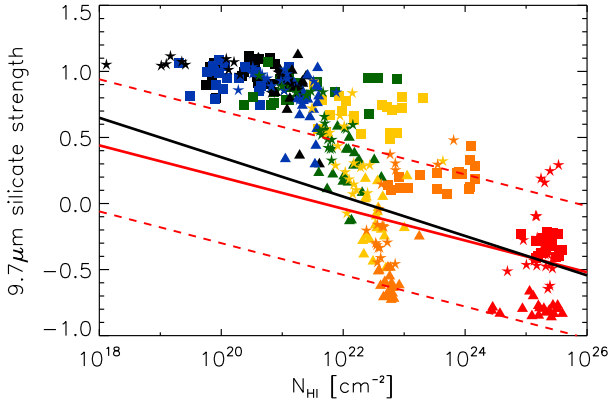


Figure 11. The silicate feature strength plotted as a function of the neutral hydrogen column density for model ER01 (squares), ER10 (triangles) and ER20 (stars) at inclination angles of 0° (black), 30° (blue), 60° (green), 70° (yellow), 80° (orange) and 90° (red). The fit to an observed sample of active galaxies is shown as the black line, whereas the red line is a fit to the sub-sample of Seyfert galaxies (Shi et al. 2006). The dashed red lines are meant to guide the eye concerning the observed scatter around the relation for the Seyfert galaxies.

$7.5\,\mu\text{m}$ and from 25.0 to $40.0\,\mu\text{m}$. These wavelength ranges are chosen such to be outside the two broad silicate features at $9.7\,\mu\text{m}$ and $18.5\,\mu\text{m}$. Being partly in the decreasing region of the SED, this choice slightly affects the determined silicate feature strengths, but we consider it the cleanest option. The distribution of observed AGNs in this diagram has been determined by Shi et al. (2006). They compiled a sample of 85 AGNs of various types for which Spitzer IRS (Houck et al. 2004) observations or ground-based measurements from the Roche et al. (1991) sample were available as well as HI column density information from X-ray spectra through the *Chandra* data archive or from literature. The resulting relationship for the full sample is shown by the black line, whereas the red line depicts the observed relation for the Seyfert galaxy sub-sample. Both show significant scatter (roughly accounted for by the red dashed lines, but compare to Fig. 3 in Shi et al. 2006 for the actual observed distribution) which was interpreted as clumpiness of the absorbing gas and dust distribution. Overplotted in Fig. 11 is the resulting distribution for our models. The inclination of the simulations is colour-coded (0° – black, 30° – blue, 60° – green, 70° – yellow, 80° – orange, 90° – red) and the various symbols refer to the three models (ER01 – squares, ER10 – triangles and ER20 – stars). For model ER10, we find a too steep slope with only a small amount of scatter up to an inclination angle of 80° , followed by a jump in column density. The reason for this is again the failed wind, leading to a geometrically thick shell of gas surrounding the central region. Such a configuration fails to explain the observed trend, as was also found in the analysis of smooth torus models (Schartmann et al. 2005), which was done in Fig. 11 of Schartmann et al. (2009). The jump in column density (but not in silicate feature strength) can be explained by the thin but very dense disc component in all the models. Whereas the neutral column density probes only the line of sight, the silicate feature strength is a superposition of the effects from the full model space (depending on optical depth along the

individual lines of sight). For the same reason, the edge-on views for models ER01 and ER20 – although having similar column densities – end up on or close to the observed relation in contrast to ER10. Whereas the scatter is too small for ER01, it is comparable to the observed scatter for the higher Eddington ratio model ER20. The reason for this can be found in the stronger time variation / intermittency of ER20 (which in the steady state is identical to a rotation of the obscuring structure along the symmetry axis), caused by the more filamentary / clumpy nature of this model (see Fig. 1 and 5).

All of the models produce too strong silicate emission features compared to the observed relation. The best adaptation of the data is given by model ER20, which seems to follow a broken powerlaw distribution, providing a good representation of the observations at large inclination angles, but a too steep slope at small inclination angles. The latter is related to the fact that the warm gas emission seems to be too extended above the high density region of the obscuring structure and probably missing clumpiness in the central region (see discussion in Schartmann et al. 2008), which might be related to too low resolution ($0.125\,\text{pc}$) of the underlying hydrodynamical simulations in this central part. Another reason for the discrepancy might also be related to the observations. Given the low spatial resolution of the Spitzer observations, the true nuclear emission feature strength of the central dusty component heated by the central source can also easily be diluted due to additional flux contributions from within the beam, e. g. caused by the host galaxy or a circumnuclear star burst. Concerning the absorption feature strength, the problem is confusion caused by additional dust extinction due to dusty filaments or clumps along the line of sight, as is e. g. the case in Centaurus A, where a prominent circumnuclear dust lane might cause additional extinction (see also discussion in Sect. 5.1, P14 and Goulding et al. 2012).

5.4 The obscured fraction

In this subsection, we introduce two methods for determining the obscured fraction of active galactic nuclei, which we subsequently apply to our set of simulations. Firstly, we use 1000 randomly chosen lines of sight to directly determine the optical depth at $0.55\,\mu\text{m}$ along radial rays (see Fig. 2). The obscured fraction is then given by the ratio of the number of rays with an optical depth larger than one (as indicated by the horizontal line in Fig. 2) to the total number of rays and is shown in Fig. 12 along the y-axis. The second method we use follows the approach of Lusso et al. (2013) (as already mentioned in Sect. 1) and derives the obscured fraction from the SEDs. The results of this derivation are given along the x-axis of Fig. 12 and will be discussed below. Concerning the first method, all data from model ER01 (black squares) – resembling the thin disc initial condition for the whole simulation time – show the expected very low obscuration fraction. For the case of model ER10 (red triangles), the obscuration fraction scatters around a high, constant value and later decreases (symbols get smaller with increasing time). This matches well the increasing trend of the $0.1\,\mu\text{m}$ light curve (Fig. 8, middle panel, squares). The correspondence of the obscured fraction to the light curve is even more evident for model ER20 (blue stars) with a max-

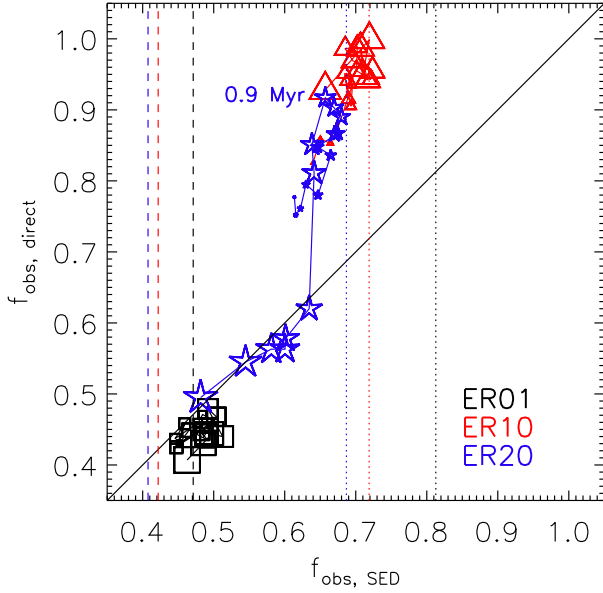


Figure 12. Obscured fraction for the models ER01 (black squares), ER10 (red triangles) and ER20 (blue stars) as determined from the SEDs plotted against the directly determined obscured fraction. The symbol size shrinks with time between the first (0.1 Myr) and the last recorded snapshot at 2.0 Myr. The vertical lines are the values for the three (effective) luminosities determined from a fit to observations by Lusso et al. (2013) for the assumption of an optically thin (dotted lines) and optically thick obscuring structure (dashed lines) calculated with Eq. 3.

imum in $f_{\text{obs, direct}}$ at the same time ($t = 0.9$ Myr) as the minimum in the short wavelength ($0.1 \mu\text{m}$) light curve (see Fig. 8, lower panel, squares).

The obscured fraction as a function of nuclear luminosity has been observationally examined by Lusso et al. (2013). By fitting the observed broadband SED and decomposing it into starburst, hot dust re-emission, host galaxy and big blue bump components, they are able to determine the ratio R of hot dust re-emission luminosity and the intrinsic AGN luminosity ($R = L_{\text{IR}}/L_{\text{UV}}$), which directly relates to the obscured fraction of AGN by (Granato & Danese 1994)

$$f_{\text{obs}} \simeq \frac{R}{1 + R(1 - p)}, \quad (2)$$

where p is an anisotropy parameter defined as the ratio between the integrated emission of the dust in edge-on view and face-on view. Using 513 type 1 AGNs from the XMM-COSMOS survey, Lusso et al. (2013) are able to fit the resulting luminosity dependence of the obscured fraction by a receding torus model with luminosity dependent scale height ($h \propto \xi$, see Simpson 2005):

$$f_{\text{obs}} = \left[1 + 3 \left(\frac{L_{\text{bol}}}{\mathcal{L}_0} \right)^{1-2\xi} \right]^{-0.5} \quad (3)$$

where $\mathcal{L}_0 = 10^{46.16} \text{ erg s}^{-1}$ and $\xi = 0.37$ for the assumption of the obscuring structure to be optically thin in the mid-infrared ($p = 1$) and $\mathcal{L}_0 = 10^{42.65} \text{ erg s}^{-1}$ and $\xi = 0.44$

for optically thick obscuring structures in the mid-infrared ($p \ll 1$). As our central source is anisotropically emitting, we replace L_{bol} with the angle averaged quantity:

$$L_{\text{bol}} = \epsilon_{\text{Edd}} \frac{2}{\pi} L_{\text{source}} \quad (4)$$

The resulting obscured fractions from this formula are shown in Fig. 12 as the vertical dotted (dashed) lines in the respective colours for the assumption of optically thin (thick) obscuring structures, clearly demonstrating the very shallow correlation with luminosity. The directly determined obscuring fractions (Fig. 12, plotted along the y-axis) are in reasonable agreement with the observationally determined values for the cases of ER10 and ER20 in the later stages of the evolution. Both models finally approach the observations for the optically thin case ($f_{\text{obs}} = 0.74$ for ER10 and $f_{\text{obs}} = 0.71$ for ER20), corresponding to the interpretation favoured by Lusso et al. (2013). However, one has to take into account that the luminosity change in our modelling approach is solely caused by a change of the Eddington ratio and not the black hole mass itself. Additionally we are investigating the low luminosity end of the observed relation, which is not very well sampled observationally. Hence, model ER01 cannot directly be compared to the observed relation (extrapolated fraction), but it shows very good correspondence to the observed value for the optically thick interpretation ($f_{\text{obs}} = 0.48$ for ER01). We should also note that as we fix the inner radius to 1 pc, independent of the sublimation distance in all models, the behaviour cannot be related to the receding torus model.

Fig. 12 also shows the obscured fraction when determined in the same way as in Lusso et al. (2013), but taking the anisotropy parameter into account. According to this analysis, all models are in agreement with the observations, as they lie within the limiting cases of optically thick ($f_{\text{obs}} = 0.48$ for ER01, $f_{\text{obs}} = 0.43$ for ER10 and $f_{\text{obs}} = 0.42$ for ER20) and thin ($f_{\text{obs}} = 0.83$ for ER01, $f_{\text{obs}} = 0.74$ for ER10 and $f_{\text{obs}} = 0.71$ for ER20) obscuring structures in AGNs. Whereas model ER01 is consistent with the observations assuming an optically thick obscuring structure for mid-IR emission, model ER10 coincides with the observations, interpreted as an optically thin obscuring structure. Whereas model ER01 gives roughly consistent results for both methods, this is only the case in the beginning of the evolution for model ER20. The directly determined fraction is higher compared to the one determined from the SEDs for model ER10 and in the equilibrium state of model ER20. This clearly shows the difficulties of the interpretation of the obscuring fraction with the help of SEDs for the case of our models.

6 DISCUSSION

Recent detailed investigations of a sample of nearby Seyfert galaxies observed with MIDI reveals a diversity of obscuring structures in AGNs (Burtscher et al. 2013). Whereas a fraction of the sources show clear signs of elongations (mostly in polar direction for the best-studied cases), others can be well explained by a symmetric brightness distribution. A similar behaviour is not only found in the Eddington ratio

study presented in this work (Fig. 5), but already in the dynamical evolution of the single models with time. One can easily imagine that an additional variation of the (remarkably few) model parameters (e. g. the black hole mass, see Table 1) will add to this diversity in appearance. Hence, a strict one-to-one comparison with observations is not useful at this point, but we mainly restrict ourselves to comparing to average observed properties.

There is a striking similarity of the filamentary structure of the thin disc component of the model (Fig. 3) with the filaments and spiral-like patterns found in the extinction maps for nearby Seyfert galaxies (Prieto, Maciejewski & Reunanen 2005, P14), but on larger scales. These are the typical features caused by disc instabilities (e. g. Toomre 1964; Wada 2001; Behrendt, Burkert & Schartmann 2014), which enable the gas to be fed towards the central parsec scale region.

One caveat of the radiative transfer simulations used in this paper is the comparatively low resolution (0.125 pc) of the underlying hydrodynamical simulations in the central region. This does not allow to resolve the small-scale structure there, which leads to a smearing out of the density distribution and might be partly responsible for the deviations seen in the comparison to the observed silicate feature strength versus column density relation. We were therefore forced to set a large inner radius of one parsec, which is outside the expected dust sublimation radii for most of the grain species we use and hence no grain dependent sublimation can be applied in these simulations. After a detailed analysis of the temperature distributions, we find that in model ER01 none of the dust reaches above our assumed sublimation temperatures (1000 K for silicate and 1500 K for graphite dust). In model ER10, a fraction of 8.3×10^{-7} of the total dust mass is up to a factor of 1.3 above the sublimation temperature and in model ER20 this amounts to a fraction of 2.9×10^{-6} with a maximum temperature up to a factor of 1.5 above the sublimation temperature. The grain dependent sublimation was found to influence especially the near-IR emission properties (most important for the low Eddington ratio model ER01, in which the nominal dust sublimation radius is well below the inner radius) as well as the strength of the silicate emission feature of the models (Schartmann et al. 2005) and should be further elaborated in upcoming high-resolution simulations. To this end, a quantitative and detailed comparison to interferometric measurements of the two nearest Seyfert galaxies NGC 1068 and the Circinus galaxy is currently not feasible, but this should be done with the next generation physical models, due to the much better constraining power compared to a sole comparison to SEDs. This is even more the case for the upcoming Matisse instrument (Lopez et al. 2012) given its imaging and multi-band capabilities.

7 CONCLUSIONS

Recently, Wada (2012) proposed a physical model for the evolution of the gas and dust distribution within AGN cores, where X-ray heating in combination with radiation pressure on dust leads to the establishment of a *radiation-driven fountain* process in an initially thin disc. A vortex motion of the gas is created, where the back-flowing part drives turbulent motions in the disc, which significantly increases

its scale height. The idea of this article is to connect this physical model with observational properties. To this end we feed the resulting time-dependent gas distribution into the Monte-Carlo dust radiative transfer code RADMC-3D in order to calculate images and spectral energy distributions (SEDs), which we compare to available observations. This enables us for the first time to derive the time evolution of the dust emission from an obscuring structure around an AGN. The parameters are chosen such to resemble nearby Seyfert galaxies, which are the nearest and hence best observed active galaxies. The input density distributions are characterised by a three-component structure: (i) a very dense, but geometrically thin disc, which is structured by gravitational instability into clumps, which get stretched into filaments by tidal forces and (ii) a surrounding atmosphere – responsible for most of the obscuration – with significant sub-structure formed by column density instability mediated by radiation pressure, which collimates a (iii) low density outflow along the rotation axis. This multi-component morphology is also reflected in the temperature structure, strengthened by the applied $|\cos(\theta)|$ radiation characteristic. The latter leads to dramatic differences when observing at different wavelengths: the appearance in most cases changes from a vertically elongated structure – tracing the outflow cone – at short wavelengths to a disc-like appearance at longer wavelengths. The intermittent behaviour of the flow is directly visible in the image series in the mid-IR as well as indirectly in the SEDs as well, which naturally show the strongest time-dependence at short wavelengths close to $0.1 \mu\text{m}$ where both the source spectrum as well as the opacity curve has its maximum. From a study of various Eddington ratios for the central luminosity we favour those which create a strong and fast outflow, with low column density close to the poles and a wide opening angle of the obscuring material (model ER20 for our sample). These typically show mid-IR images which are elongated in polar direction (partly displaying X-shaped features), which seems to be in agreement with recent findings with the help of the MIDI instrument for a number of nearby Seyfert galaxies. However, when comparing to the silicate feature strength versus column density relation, we find good agreement at high column densities, but too strong silicate emission features at low inclination angles and column densities. The latter being related to too much emission from dust within the funnel or from the funnel walls (partly with unfavourable morphology) or by a too small amount of clumpiness, which might be caused by too low resolution in the nuclear region close to the radiation source or the missing grain dependent sublimation due to a too large inner radius.

In summary we find good agreement of the proposed physical model for the build-up and evolution of obscuring structures in AGNs with available observations. In future, we plan to compare the revealed three-component structure (as found in the best-fit model ER20) of a higher resolution simulation also covering the sublimation region to high spatial resolution interferometric observations in various wavebands.

ACKNOWLEDGMENTS

We are grateful to Hagai Netzer for helpful discussions and for providing us with an extension of the composite SED presented in Mor & Netzer (2012) towards shorter wavelengths prior to publication. A detailed and constructive report by an anonymous referee helped to improve the publication. We thank C. P. Dullemond for making RADMC-3D³ publicly available and for his continuous support with the code. This work was supported by the Deutsche Forschungsgemeinschaft priority program 1573 (“Physics of the Interstellar Medium”). KW is partly supported by JSPS KAKENHI Grant Number 23540267. AP thanks for the hospitality of the Max Planck Institute for extraterrestrial Physics and the CAST group.

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